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Performance of a Family of Omni and Steered Antennas for Mobile Satellite Applications

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ABSTRACT

This paper describes the design and performance of a family of vehicle antennas developed at JPL in support of an emerging U.S. Mobile Satellite Service (MSS) system. Test results of the antennas are presented. Trends for future development are addressed. Recommendations on design approaches for vehicle antennas of the first generation MSS are discussed.

INTRODUCTION

The emerging U.S Mobile Satellite Service system will provide telephone and data services for a variety of users across the Continental United States (CONUS). To implement this system, high performance vehicle antennas are needed to provide the communications link between the satellite at the geostationary orbit and the mobile vehicles on the ground. Over a number of years, JPL has been conducting research and development on a family of vehicle antennas for meeting the requirements of diverse potential users. These antennas are required to be circularly polarized and to provide coverage from 20° to 60° above the horizon in elevation, and a full 360° in azimuth. They are to operate at the L-band, 1.5450 to 1.5590 GHz for receive, and 1.6465 to 1.6605 GHz for transmission. Both low-gain omni-directional and medium-gain steerable antennas have been developed. Test results of earlier designs of these antennas have been summarized and reported in Ref. [1]. This papers reviews the designs and addresses recent development of the antennas.

OMNI-DIRECTIONAL ANTENNAS

The purpose of developing omni-directional antennas is to provide users with antennas that are simple, reliable, and low cost. Circularly polarized omni antennas of crossed drooping-dipole, quadrifilar helix, and microstrip designs have been developed[1]. These antennas were found to be able to provide 3.5 to 6.0 dBic gain for CONUS coverage.

The crossed drooping-dipole antenna is most versatile in use. By varying the separation between the dipole elements and the ground plane (top of vehicle) the elevation pattern can be adjusted for optimum coverage for the coverage region of interest. Both right-hand circularly polarized (RCP) and left-hand circularly polarized (LCP) designs were developed. Figure 1 shows an LCP design used in the AUSSAT mobile experiment, described below. The antenna provides a peak gain of 5.3 dBic at the AUSSAT look angle of 55° above the horizon.

STEERABLE ANTENNAS

Medium-gain steerable antennas were developed for mobile vehicles. The purpose of the development is two-fold: (1) to provide higher antenna gain for the mobile terminal, and (2) to provide a directive beam to effect sufficient intersatellite isolation for interference-free communications. The goals are to achieve: (1) a minimum of 10 dBic gain throughout the elevation angles 20° to 60° above the horizon, and (2) 20 dB intersatellite isolation for two satellites with opposite polarization placed approximately 30° apart in the geostationary orbit. Two classes of steerable antennas have been designed and breadboarded. These are the electronically steered phased-array antennas and the mechanically steered tracking antennas. Low cost and low profile were the two principal drivers in designing these antennas.

Electronically Steered Phased Array Antennas

Phased array antennas were developed principally to provide a thin antenna that can be installed conformal to the top of the vehicle for aesthetic or security reasons. These antennas are well known for their complexity and high cost. As a result, emphasis was placed, in addition to meeting the RF and pointing requirements, on the selection of manufacturing techniques, materials, and component types, so as to keep the cost down.

Two RCP phased-array antennas were separately developed by Ball Aerospace Systems Division[2] and Teledyne Ryan Electronics[3] through contracts and technical guidance by JPL. The antennas developed by these two companies, as shown in Figure 2, exhibit several common features. Both antennas use 19 radiating elements with 18 3-bit diode phase shifters. The RF construction of both antennas employ the "layer" approach. Satellite tracking is achieved in the azimuth plane by the sequential lobing technique and in the elevation plane by a slow amplitude search mechanism. The tracking systems of both antennas are augmented by an angular rate sensor for combating short signal drop-outs or fades.

There are also several distinct differences in technology and design between the two antennas developed by the contractors. Ball uses a dual-resonant stacked half-inch-thick circular microstrip element to cover both the transmit and receive bands, while Teledyne employs a quarter-inch-thick stripline cavity-backed crossed-slot radiator. The microstrip element has a 3-dB beamwidth of about 90°, and the crossed-slot element has a beamwidth of 140°. The crossed-slot element is thinner and allows the array beam to scan lower in elevation due to its wider element beamwidth. The dual stacked microstrip element is lower in cost because of its simplicity and the use of low-cost foam material. Another difference between the two antennas is that Teledyne uses the switched-line 3-bit diode phase shifters, while Ball employs the hybrid reflection/loaded-line type 3-bit phase shifters. The former use 6 diodes each, while the latter require 12 diodes each. The hybrid phase shifter has slightly higher insertion loss and phase error as compared to the switched-line design. Overall, it seems that Ball emphasized a lower cost design, while Teledyne concentrated on performance.

In addition to the RCP phased arrays developed by Ball and Teledyne, an LCP unit was also produced by Teledyne under a follow-on JPL contract. This LCP unit was successfully tested in the AUSSAT mobile experiment in Australia with the Japanese satellite ETS-V which has an LCP antenna. The construction and design of this Teledyne LCP antenna are exactly the same as the RCP unit except the hybrid circuit where the two orthogonal ports are interchanged. As a result, the performance of the LCP unit is very similar to the RCP antenna. Several important characteristics and measured performance of the Ball and Teledyne phased array antennas are listed in Tables 1 and 2. The measured radiation patterns of the LCP phased array antenna are shown in Figure 3.

Mechanically Steered Tracking Antennas

Mechanically steered tracking antennas were developed for the purpose of providing a tracking antenna with considerably lower cost than the phased array antenna. The challenge here is to achieve a low-profile and low-cost design in addition to meeting the RF and pointing requirements.

Three mechanically steered tracking antennas were developed. The original design was a tilted array antenna developed entirely at JPL[4]. An iteration of this antenna produced a lower-profile, lower-weight antenna by redesigning the pointing platform and employing integrated stripline feed circuitry[5]. Another antenna was a hybrid mechanically/ electronically steered antenna built by Teledyne Ryan Electronics under contract with JPL[6].

Figure 4 presents a pictorial view of the two mechanically steered antennas. Both antennas employ the same monopulse technique for tracking the satellite in azimuth. The full antenna system with either antenna installed is effectively described by the block diagram in Figure 5. The array is designed for the simultaneous transmission and reception of communication signals as well as the reception of the "error" signal required for monopulse tracking. The functioning of the antenna RF subsystem in the receive mode is summarized as follows.

The radiating array is divided into two equal subarrays, each composed of two radiating square microstrip patch elements. The signals from the two subarrays pass through a sum/difference hybrid whereby their sum and difference are obtained. The difference or "error" signal is then channeled through a one-bit (0-180 degrees) phase shifter which will be modulated at a rate of between 200 to 4800 Hz. It is then passed through a 30-dB ferrite isolator. The difference signal is then combined with the sum signal via a 10-dB coupler in which the difference signal strength is reduced by approximately 10 dB before combining with the sum signal. The combined output of the coupler is then passed to the single-channel rotary joint. Thus, since the difference signal is modulated before addition to the sum signal, it can be extracted from the composite signal at the receiver by standard filtering techniques. This normalized "error" signal is then supplied to the pointing control circuitry, which commands a stepper motor to rotate the antenna array in order to maintain pointing toward the source of the incoming signal. This is basically the closed-loop operation of the antenna system. An azimuth rate sensor is used to provide for the open-loop operation of the system, namely to maintain pointing during the tracking phase when the received signal fades below a prescribed threshold.

The design and performance of the original JPL tilted array antenna has been reported extensively. The antenna was successfully tested in the Tower experiments at Erie, Colorado, and Satellite experiments at Santa Barbara, California.

The success of the original breadboard antenna led to additional research aimed at reducing the antenna height as well as integrating some of the discrete RF components into the stripline-fed microstrip patch array. Two stripline layers flush-mounted behind the microstrip patch array provide most of the required RF circuitry. The quadrature hybrids for four microstrip patches are on one layer, while the array divider/combiner, the sum/difference hybrid and the sum/ difference channel coupler are all implemented on a second layer. Discrete components are used only for the modulator and the isolator. In addition to somewhat improved RF performance, this integrated design is lighter and less expensive. The major modification of the pointing platform involved the use of a very low profile pancake stepper motor and associated gear drive mechanism, as well as a low-profile rotary joint. A low-cost rate sensor by ETAK corporation was also incorporated in the design. The modification of lower platform provided a height reduction from 23 to 15 centimeters and a weight reduction by about 4.5 Kg for the overall antenna system.

Both RCP and LCP units were breadboarded for the reduced-height antenna. They have approximately the same RF performance except for the sense of polarization. The LCP units were used in the AUSSAT mobile experiment. Several important characteristics and measured performance of the antennas are listed in Tables 1 and 2. The measured radiation patterns of an LCP unit are shown in Figure 5. The same antenna was also tested for power-handling capability. Over 20 watts of CW RF power was applied to the antenna at the rotary joint input. The antenna successfully passed the test without problems.

For further reducing the height of the antenna, a low-profile planar hybrid mechanically/electronically steered tracking antenna was fabricated by Teledyne Ryan Electronics under contract with JPL. Figure 6 shows a pictorial view of the antenna using 32 crossed-slot stripline elements and pancake stepper motor drive. The array elements are arranged with complete symmetry with respect to the two major axes of the array. Two phase shifters connected to the two identical halves of the array provide for sequential lobing in azimuth. Another two pairs of phase shifters are used for beam switching in elevation. Signal acquisition is based on seeking the maximum received signal strength.

This hybrid-scanned antenna did not achieve the RF performance goals. Factors such as high circuit losses, array grid configuration, and mutual coupling effects contributed to serious performance degradation. The design, however, seems basically sound; and a more careful implementation with some modifications can provide a successful antenna.

Noise Temperature Measurement

The noise temperature of the developed antennas have been measured using the set-up as shown in Figure 7[7]. The antenna under test is mounted to the roof of the Pilot Field Experiment (PiFEx) van and connected via a series of low noise amplifiers and filters to a spectrum analyzer. The noise temperature of the antenna is calculated by comparing the noise power read on the spectrum analyzer when the antenna is connected to the subsequent amplifiers and when a 50-ohm load is connected to the same amplifiers.

Both RCP and LCP units of the antennas were measured. Table 1 lists the measured noise temperature of the RCP units and Table 2 shows those of the LCP units used in the AUSSAT mobile experiment. The measurements were taken at the JPL Mesa Antenna Range. Table 2 also shows the corresponding mobile receiver G/T assuming that the antenna is connected to an amplifier with a 2.0 dB noise figure by a cable with a loss of 0.3 dB. The noise temperature of the receiver and cable (without the antenna) is 203K.

AUSSAT ANTENNA EXPERIMENTS

The LCP units of the reduced-height mechanically steered tilted array antenna, the Teledyne phased array antenna, and the crossed drooping-dipole antenna were field tested during the AUSSAT mobile experiment. Overall, the antennas performed very well, especially in providing the automatic antenna pointing function. However, both the mechanical antenna and the phased array antenna (after 5 hours of operation) developed excessive noise when transmitting high power. The antennas were therefore used in receive mode only, with the crossed drooping-dipole antenna as the transmitting antenna. In this manner, a great variety of experiments were conducted during which the antenna pointing systems of both antennas performed flawlessly.

The original JPL mechanically steered tilted array antenna was successfully tested in duplex mode for the Tower experiments at Erie, Colorado, that required less transmit power. The noise associated with high power transmission has been traced to the monopulse modulator (phase shifter)[8]. The commercially purchased unit switched too fast for this application, generating extremely high order harmonic of the monopulse tone, which fell into the receive band. This was resolved by redesigning the modulator with slower phase transitions by using slower diodes and slower charge sweeping of the diode junction. Figure 8 shows the new modulator circuit and the noise level before and after the replacement. The noise in the Teledyne phased array antenna has been traced to one of the diode driver integrated circuits that had disconnected from the circuit and possibly microplasma noise of the PIN diodes.

CURRENT DEVELOPMENT ACTIVITIES

To further strive for low cost, low profile vehicle antennas, development work for low cost planar arrays are being carried out at JPL. These are the planar microstrip Yagi array, and the ANSERLIN (Annular Sector Radiating Line) array, as shown in Figure 9. These arrays are designed for direct replacement of the tilted array of the reduced-height antenna shown in Figure 4. The resulting antenna is nearly conformal (~ 4 cm high). A preliminary version of a mechanically steered tracking antenna using the planar microstrip Yagi array is shown in Figure 10. The antenna is currently under test.

The two types of arrays are expected to be low cost in that they both need only a very simple beamformer. In lieu of feeding each element, it is only necessary to feed rows of linear arrays. The planar Yagi array is based on mutual coupling effect, and the ANSERLIN array is based on travelling wave type of operation. The details of the design and the theory of operation can be found in the companion papers [9, 10] of this Conference.

A planar microstrip Yagi array designed to meet the specifications of the MSS has been breadboarded. The array meets the 10 dBic minimum gain requirement for CONUS coverage.

CONCLUSIONS AND RECOMMENDATIONS

Based on the design configurations and performance figures of vehicle antennas developed to date, the following observations are made.

The omni-directional crossed drooping-dipole antenna is small, simple, reliable, and low cost. Although the antenna is relatively low in gain, it does provide a reasonable antenna G/T. The antenna may not be adequate for voice applications, but it is certainly good for low rate data transmission. This antenna will certainly become a very important component for mobile communications.

The electronically steered phased arrays are conformal and therefore are aesthetically pleasing and good for security applications. But at this stage, they are of high cost and have some reliability problems. The cost drivers of the antenna are dielectric circuit boards, phase shifters, diodes, beam-pointing electronics, and assembly labor. Although their costs can be reduced by significant increase in market demand, new technologies are needed to develop low cost manufacturing processes and reliable components for minimizing the cost drivers and improving reliability.

The mechanically steered tracking antennas offer similar gain and G/T as phased array antennas, but they are considerably lower in cost. Although existing designs are relatively high-profile, the success of the low-cost, low-profile arrays such as planar microstrip Yagi, or ANSERLIN, or the like, will lead to a conformal antenna similar in height to the phased array antenna.

Comparing the relative merits, it seems that for the application to the first generation MSS, the mechanical steered tracking antennas using low-cost planar arrays would be a logical choice. However, phased array antennas could also provide distinct services when and if the cost can be brought down. Research should continue to develop new low-cost manufacturing processes and new reliable components/devices so that the phased array antenna can be a choice for future generations of MSS.

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Table 1. Performance of vehicle antennas designed for CONUS coverage

Antenna[1]	Gain[2] (dBic)	Intersatellite Isolation[3] (dB)	Noise Temperature (K)	Size		Estimated Manufacturing Cost[4] ($)
				Height (cm)	Diameter (cm)	
Mechanically steered tilted array antenna						
Original design	≥10.0	≥24	172	23	51	600
Reduced-height design	≥10.0	≥24	164	15	51	600
Electronically steered phased array antenna						
Ball design	≥ 8.0	≥19	161	3.3	61	1600
Teledyne design	≥ 8.0	≥25	186	1.8	54	1800
Crossed drooping-dipole antenna	≥ 4.0	≥10	45	≤12	8.0	50

1 All antennas are right-hand circularly polarized.
2 Averaged in azimuth at various elevation angles of interest for both transmit and receive frequencies.
3 For two satellites with opposite circular polarization separated by 30° in geostationary orbit.
4 Based on producing 10,000 units per year over a five-year period.

Table 2. Performance of vehicle antennas designed for AUSSAT mobile experiment

Antenna[1]	Gain (dBic)	Noise Temperature (K)	G/T[2] (dBic/K)
Reduced-height mechanically steered titlted array antenna (stripline-fed)	11.3	134	-14.0
Teledyne phased array antenna	10.5	186	-15.4
Crossed drooping-dipole antenna	5.3	37	-18.5

[1] All antennas are left-hand circularly polarized.

[2] Based on receiver and cable noise temperature of 203K.

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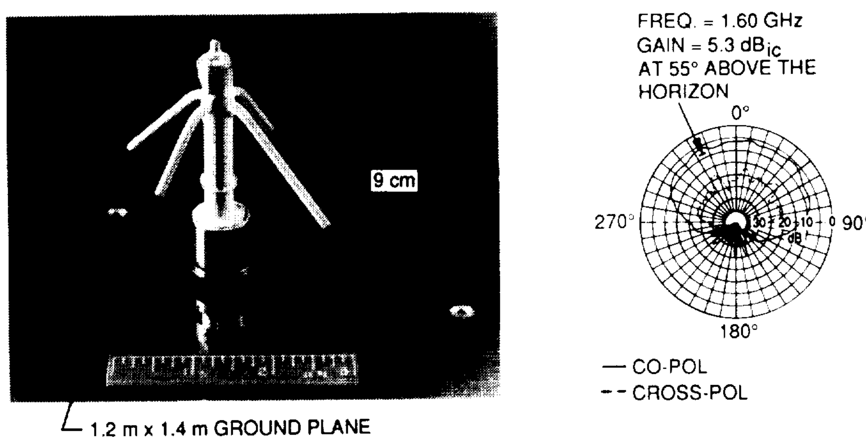

ANTENNA DESIGN

ELEVATION PATTERNS

Figure 1. Crossed Drooping-Dipole Antenna, LCP

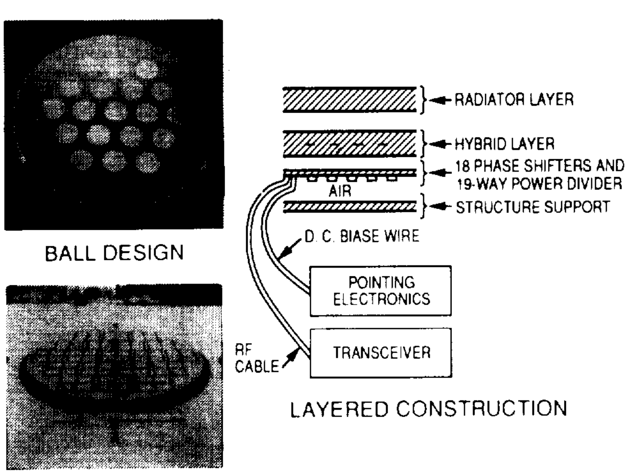

Figure 2. Electronically steered phased array antennas

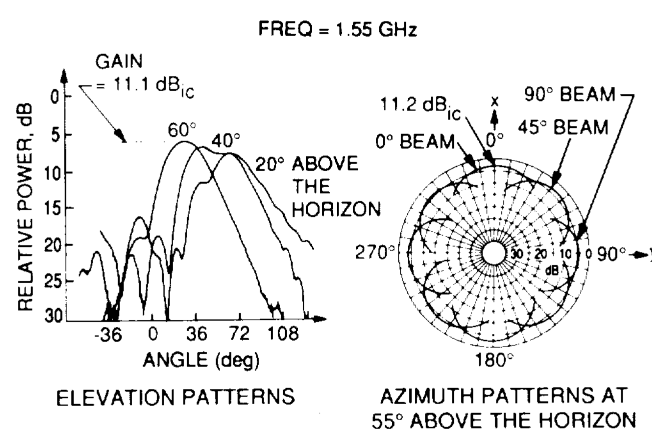

Figure 3. Co-pol patterns of Teledyne phased array antenna, LCP

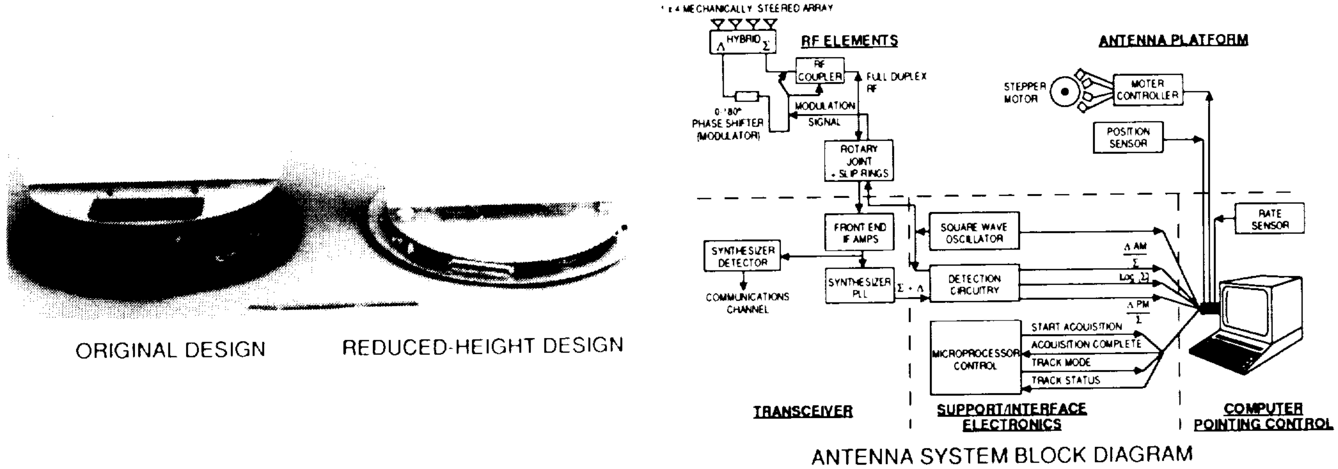

Figure 4. Mechanically steered tilted array antennas

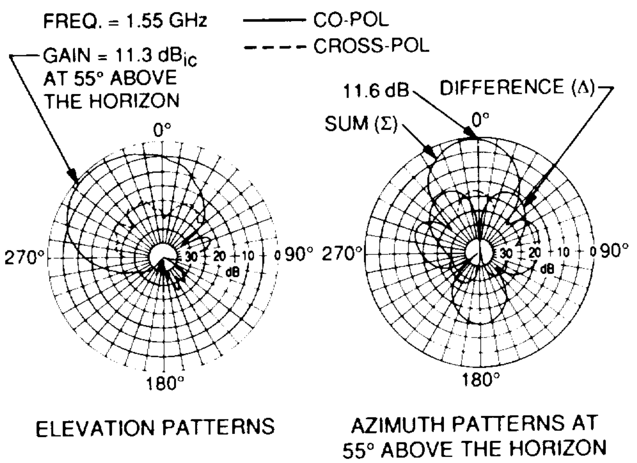

Figure 5. Radiation patterns of reduced-height mechanically steered tilted array antenna, LCP

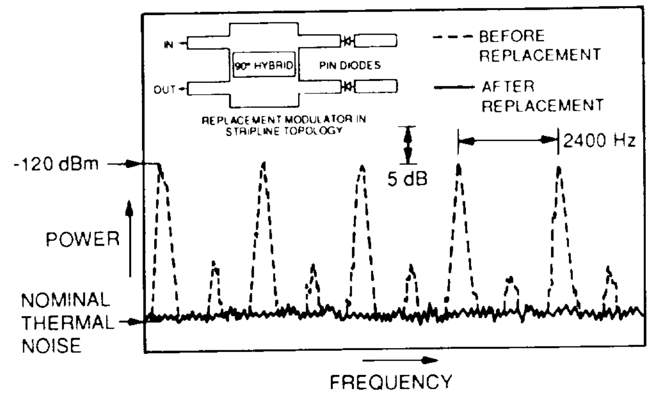

Figure 8. Antenna noise before and after replacement of monopulse modulator

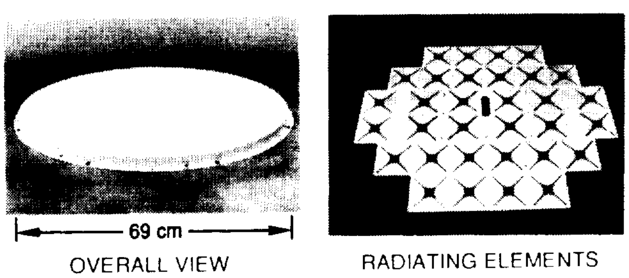

Figure 6. Mechanically steered planar array antenna (Teledyne design)

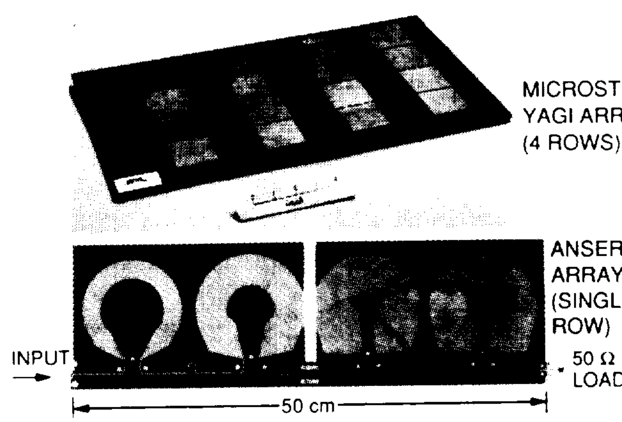

Figure 9. Low cost planar arrays

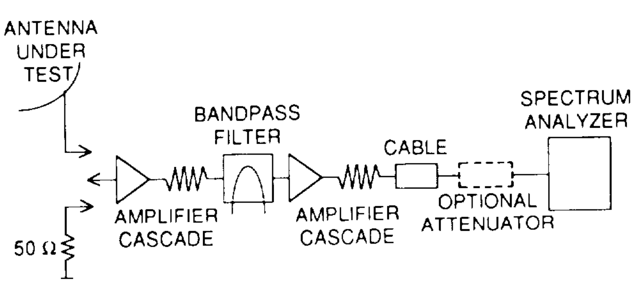

Figure 7. Noise temperature measurement set-up

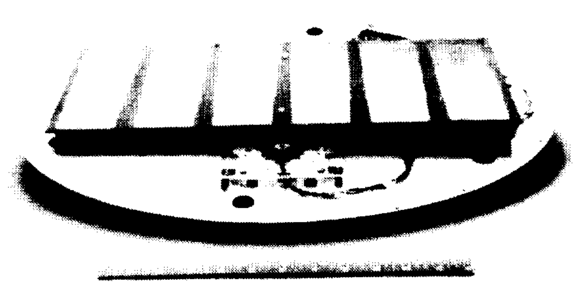

Figure 10. Conformal mechanically steered tracking antenna